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EVALUATION OF THE LEFT TURN RED ARROW

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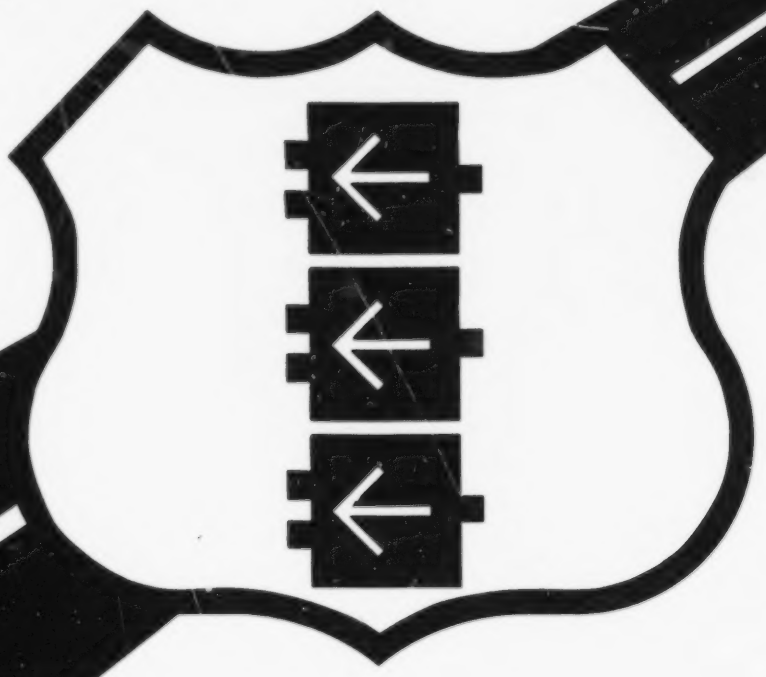
Final Report



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FOREWORD

The objective of this study was to determine whether the use of the red turn arrow instead of the red circular indication created a safety problem because of a lack of understanding by motorists. The report will be of interest to traffic engineers involved in controlling traffic by traffic signals.

For those jurisdictions which have never previously used the red arrow in their traffic signalization systems, the results showed that the violation rate was 8.2 percent for the red circular as compared to 6.5 percent for the red arrow. It was further found that the violation rate for the red arrow was significantly lower than the red circular indication at the one percent level.

For those jurisdictions which have previously used red arrows, similar results were found. The observed violation rates were 6.7 and 5.7 percent for the red circular and red arrow, respectively. Again, the red arrow was significantly lower than the red circular but only at the 5 percent significance level.

Sufficient copies of the research report are being distributed to provide two copies to each regional office, one copy to each division office, and one copy to each State highway agency. Direct distribution is being made to each division office.

Charles F. Scheffey
Director, Office of Research

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16. Abstract

This report focuses on the question whether the use of red turn arrows in lieu of red balls can create a safety hazard because of motorists' misinterpretation of the device. Traffic violations of the red arrow and and red ball indications were observed at 15 intersections. Sites were selected from Washington, D.C.; Delaware; Westchester County, New York; Minnesota; and Colorado. Intersection types included the cross, wye, and tee. Violation rates, defined as the number of cycles in which at least one violation (turning on the red) occurred during a cycle divided by the total number of cycles observed, were calculated for both the red arrow and red ball. The study concludes that in those jurisdictions using the red arrow for the first time, the violation rate is 6.5 percent for the red arrow as against 8.2 percent for the red ball. For jurisdictions which had used the red arrow previously, the violation rates are 5.7 and 6.7 percent for the red arrow and red ball, respectively. In both situations, the differences are statistically significant at the 5 percent level.

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Officials of Washington, D.C., the states of Delaware, Minnesota, and Colorado, and Westchester County, New York are especially acknowledged for providing the sites used in the conduct of this study.

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CHAPTER I
SUMMARY

The primary objective of this study was to determine if the use of the red left turn arrow indication is an unsafe traffic control device, compared with the circular red indication when used for the same purpose. The traffic engineering community is concerned as to whether the red turn arrow is inherently confusing -- the arrow meaning go and red meaning stop --.

The study involved a "before" and "after" analysis in which the red ball was substituted by the red arrow. Signal cycles and vehicle violation of the red indication were observed at intersections with separate turn signals. Fifteen study approaches were selected in Washington, D.C.; Delaware; Westchester County, New York; Minnesota; and Colorado. These sites provided observations of more than 17,900 cycles. Intersection types include the cross, "Y", and "T". The experimental factors of the sites include simple and complex signal phasing, pedestrian signals, various signal mounts, exclusive turn signals, protective-permissive left-turns, the red arrow, the red ball, as well as supplementary turn signs. Observations were made during peak, off-peak, and night-time traffic conditions.

The statistical analysis used the signal cycle as the basis for the experimental unit. For each cycle, either no violation occurred, or one or more violations occurred. Thus, for each setting of the experimental factors, the violation factor counted the number of cycles in which at least one red violation occurred on the first level, and the number of cycles in which no red violations occurred on the second level. All cycles with no vehicles were excluded from consideration.

The study uncovered no evidence that the red arrow is unsafe or more unsafe than the circular red indication when used for the left turn. On the contrary, a statistical analysis of field data provides the basis for the following conclusions:

1. The left turn red arrow is more effective than the red ball in most left-turn situations where special turn signals and exclusive turn lanes are provided.

2. The left turn red arrow is particularly more effective at "T" than at other types of intersections.

3. The left turn red arrow is more effective than the red ball during night-time.

4. The effectiveness of the red left turn arrow is demonstrated in jurisdictions with or without prior experience in using it.

These findings should eliminate the idea that the left turn red arrow is inherently confusing and unsafe.

CHAPTER II
INTRODUCTION

BACKGROUND

Traffic control devices are intended to direct and assist pedestrians and motorists in guidance as they traverse roadway facilities opened for public travel. Thus, the insurance of continuing safety, as well as orderly and predictable movements of all traffic, is the primary purpose of traffic control devices. These devices could defeat their principal purpose if they are ineffective and confusing in warning, guiding, and informing motorists and pedestrians.

In their continuous effort to improve traffic safety, traffic engineers have developed many successful innovative traffic control devices. Generally, success is associated with applications where the movement of the traffic is natural, and where there is little or no latitude for error. Yet, there are some innovative traffic control devices whose effectiveness is in doubt and may well be communicating ambiguous messages. Among such devices is the red arrow used as a signal indication. With the variation in the use of red arrows in turn signals across the United States, the possibility of multiple and confusing interpretations of the meaning of the red arrow exists. This probably ambiguous situation is contrary to the purpose of traffic control devices, and may impact on the public through traffic accidents.

Since 1920, the National Joint Committee on Uniform Traffic Control Devices has been convening periodically to evaluate and make recommendations on traffic control devices. It has been the custom since then to maintain a manual of recommended practices which is modified as necessary following decisions made by the Committee.

Although the practice of using turn arrows in traffic signals dates back to the 1930's[8], it was not until recently that the Committee included recommendations on the use of red arrows in the Manual On Uniform Traffic Control Devices (MUTCD)[21]. Today, the MUTCD is respected as the singular document of national significance for guiding states and municipalities in the use of many types of traffic control devices.

While the majority of recommendations of the MUTCD have been adopted by states and local jurisdictions, there are many jurisdictions which have taken exception to some recommended applications. Thus, the use of red arrows in traffic signals, as recommended by the MUTCD, has received varying acceptance among jurisdictions.

The MUTCD advances the following meanings to the steady circular red and arrow signal indications:

Steady red indications shall have the following meanings:

(a) Vehicular traffic facing a steady CIRCULAR RED signal alone shall stop at a clearly marked stop line, but if none, before entering the crosswalk on the near side of the intersection, or if none, then before entering the intersection and shall remain standing until an indication to proceed is shown except as provided in (c) below.

(b) Vehicular traffic facing a steady RED ARROW signal shall not enter the intersection to make the movement indicated by the arrow and, unless entering the intersection to make a movement permitted by another signal, shall stop at a clearly marked stop line, but if none, before entering the crosswalk on the near side of the intersection, or if none, then before entering the intersection and shall remain standing until an indication permitting the movement indicated by such red arrow is shown except as provided in (c) below.

(c) Except when a sign is in place prohibiting a turn, vehicular traffic facing any steady red signal may cautiously enter the intersection to turn right, or to turn left from a one-way street into a one-way street, after stopping as required by (a) and (b) above. Such vehicular traffic shall yield the right-of-way to pedestrians lawfully within an adjacent crosswalk and to other traffic lawfully using the intersection.

(d) Unless otherwise directed by a pedestrian signal, pedestrians facing a steady CIRCULAR RED or RED ARROW signal alone shall not enter the roadway[21].

In addition to requiring that the steady red arrow be used only in signal faces containing a steady yellow arrow as well as a green arrow indication, the MUTCD also recommends that the steady red arrow be used in lieu of the circular red indication as follows:

Steady RED ARROW, YELLOW ARROW and GREEN ARROW indications may be used in lieu of the corresponding circular indications at the following locations:

(a) On an approach intersecting a one-way street.
(b) Where certain movements are prohibited.
(c) Where certain movements are physically impossible.
(d) On an intersection approach which has an exclusive lane for turning movements.
(e) Where turning movements are "protected" from conflicting movements by other indications or by the signal sequence.
(f) Where all the movements on the approach do not begin or end at the same time and where indications for the turning movements will also be visible to traffic with other allowable movements.[21]

Supplement III of the Uniform Vehicle Code (UVC) requires motorists facing a steady red arrow to stop then cautiously enter the intersection, and turn left from a one-way street into another one-way street, or to turn right, providing that there is no sign prohibiting turns. In this situation drivers are required to yield the right-of-way to vehicles and pedestrians in the intersection.[24] Generally, both the MUTCD and the UVC hold a common position regarding motorists' behavior at intersections where red arrows are used.

Rejection of the MUTCD position on the red arrow in traffic signals is sporadic among all levels of jurisdictions. Yet there are jurisdictions with strong feelings about the positive value of the red turn arrow as a safe traffic control device. Among these jurisdictions are the states of Minnesota, Massachusetts and Delaware, as well as such cities as Sacramento, Alhambra, New Port Beach in California, and Washington, D.C. Most jurisdictions -- cities, counties and states -- however, have rejected the MUTCD-UVC recommendations on the use of the red arrow because of the uncertainty of its effectiveness as a traffic control device. This and other reasons are discussed in Chapter III. However, it is clear that the current sporadic usage of the red arrow undermines the potential safety benefit which can be derived by uniformity in practice. Moreover, the non-conclusiveness of limited studies[13][22] which attempted to identify advantages in the use of the red arrow has perpetuated arguments against it. These studies are scheduled for discussion in the next chapter.

OBJECTIVES

The goals of this study are the assessment of the safety significance of using red turn arrows in traffic signals and the development of a

better understanding of their advantages and disadvantages as a traffic control device. These goals are accomplished through the following research objectives:

1. To determine if the use of the red turn arrows in lieu of the circular red indication in traffic signals results in safety hazards at locations where turn signals are separate from through signals.
2. To develop guidelines for the application of red arrows in turn signals which are separate from through signals.

SCOPE OF WORK

The accomplishment of the stated objectives was pursued by first investigating the state-of-the-practice regarding red turn arrows in traffic signals. A sample of nine states was selected for discussions with practicing traffic engineers, knowledgeable about the usage of red arrows within their jurisdictions. Discussions involved state, county, and city officials in north, south, west and central United States. A literature review supplemented the information provided by government officials.

An experimental plan was developed for collecting and analyzing data related to several hypotheses based on the major safety concerns of practitioners. The data collection activity was limited to no more than nine states. The selection of sites was based on funding constraints, as well as the willingness of jurisdictions to facilitate the study.

The experiments involved "before" and "after" field observations of selected traffic conflicts involving turning vehicles during the red arrow and ball indications at intersections with separate turn signal heads. At each study site the shape of the red indication was changed before collecting the "after" data. Field sites were located in Washington, D.C., Delaware, New York, Minnesota, and Colorado. Attempts to obtain sites in western and southern United States were not successful. The intersections studied were "Y", "X", and "T" types. The traffic control characteristics of the study sites include simple and complex signal phasing, pedestrian signals, various signal mountings, exclusive

turn signals and lanes, protective-permissive left turns, as well as supplementary turn signs. Observations were made during peak, off-peak, and nighttime traffic conditions.

The combined findings of the literature review, practicioners' comments, and the statistical analysis of the field data form the framework for the concluding suggestions on the use of red turn arrows in traffic signals.

CHAPTER III
STATE-OF-THE-PRACTICE

LITERATURE REVIEW

In Chapter II, the position held by the Manual On Uniform Traffic Control Devices and the Uniform Vehicle Code and Model Traffic Ordinance regarding the use of red turn arrows in traffic signals was discussed. In this section, other pertinent documented research is presented.

The use of the red turn arrow as a traffic signal indication is not new. In the 1960's Wilmington, Delaware, had been accustomed to use of the red arrow, especially the right-turn arrow, to emphasize the need for motorists to bring their vehicle to a perfect stop at intersections where pedestrian signals are deployed. Thus, the red turn arrow, in Wilmington and probably in other cities in Delaware, has had a long tradition of field applications.

A select committee of experienced traffic engineers of the Institute of Transportation Engineers (ITE) studied the application of red and yellow arrows in traffic signals[8]. In its 1963 report, the committee stated that, of twelve cities studied, only a few intersections were using red arrows. One of the reasons cited for the growing interest in the red arrow turn signal was the possible confusion caused by circular turn signals which can be seen by the through traffic for which they are not intended. Identified hazardous situations arising out of a confused through traffic were false stops, occurring during the display of the circular red indication intended for the left turning vehicles, and false starts due to observation of the wrong green indication. The Committee noted that some traffic engineering officials were concerned that use of the red arrow may create an ambiguous indication; the red color meaning stop and the arrow meaning go.

The ITE Committee conducted a pilot investigation to determine drivers' reaction to 30 combinations of traffic signal indications. The target sample of individuals involved only 48 adults of the safety education classes at Chicago Teachers College. While the Committee recognized

the limitation in the experiment, it was surprised to find a large number of mis-interpretations among that apparently well educated group. Real field investigations were recommended by the Committee, as the means for drawing final conclusions on motorists' interpretation of red turn arrows.

Hulbert, Beers and Fowler[7] conducted a study to determine whether motorists fully understand the meaning of the various traffic control devices used on public roadway facilities. A sample of 3,164 motorists from all areas of the United States participated in the test program of driver understanding of 23 different scenes of 16 traffic control signs, signals and markings. The scenes were presented in film to civic and other groups across the United States, along with questionnaires. The green, amber, and red arrows were among the traffic control devices tested. The results of the study indicated that only 51 percent of the motorists fully understood the green arrow. Surprisingly, motorists understanding of red turn arrows was significantly higher. Seventy-one percent answered correctly for the red left turn arrow; 89 percent for the yellow left-turn arrow; and 75 percent for the red right-turn arrow. Pavement markings were one of the least understood areas. Whether or not above 70% comprehension is a satisfactory indication of motorist understanding of red turn arrows is a matter for debate. However, the results of this research strongly suggest that, compared with the green arrow, the red arrow is properly interpreted most of the time, and is therefore a safer traffic control device than the green arrow.

Red and yellow turn arrows were studied by Kraft et al[5] to assess their efficacy as traffic control devices. The determination of present practices via discussions with traffic engineers, the survey of a random sample of motorists on the meaning of specific signal indications, and the conduct of "before and after" field experiments were the essential approach to this arrow effectiveness study. The survey and field experiment were conducted in the Washington, D.C. metropolitan area, at a selection of intersections with span-wire, median and corner-post mounts. The selection of intersections matched the recommended use of red arrows in the Manual on Uniform Traffic Control Devices (MUTCD).

The results of the study[5] did not present strong evidence that circular red left-turn signal indications are more effective than the red arrow indication deployed in the same manner. Moreover, there was no strong conclusive evidence, even after the statistical analyses, that the red turn arrows are less safe than the circular red indication. Statistically, at a 95% confidence level, violation rates for the red circle and arrow indications were not significantly different for the intersections studied. However, the report indicated that agreement among traffic engineers on the proper use of red turn arrows is far from universal. A number of jurisdictions which do not use red arrows is listed. The level of usage in other jurisdictions is discussed. Generally, the research concluded without providing new evidence to condemn the recommendations of the MUTCD, and recommends the suggested usage of the manual.

Kraft and Van Vechten[13] studied the behavior of motorists at signals with red, yellow, and green arrows. The authors found that in spite of the "right turn on green arrow only" signing, drivers make illegal right turns at least 16.5 percent of the time. This was the result of the analysis of violations observed during the "before and after" study of sign changes at a very busy intersection in Washington, D.C. The author suspects the fully loaded nature of the cycles encouraged motorists to minimize the anticipated delay by violating the red turn indication when a serious conflict is not obvious.

Bolt Beranek and Newman[18] conducted a survey to assess motorists' understanding of traffic control devices. Among the devices tested was the steady red arrow for the left-turn. A questionnaire presented a pictorial representation of a signal head with the red left-turn arrow and questions on which type of response is allowable. Sixty-three individuals responded to the red arrow questions. Of this number, 73 percent of the motorists answered according to the intent of the proposal by indicating that they were not allowed to turn left on a steady red left-turn arrow. Twenty-two percent indicated that they were allowed to turn left after stopping at a red left-turn arrow. Sixty-three percent of the respondents correctly interpreted the blinking red left-turn

arrow as permitting a left turn with caution after stopping. Eighty-one percent interpreted the blinking red left turn arrow as allowing a left turn.

J. F. Bryant[22] examined the population expectancies for signal arrows with the hope of finding which directional codings produce the highest amount of consistency in responses. As reported[22], no details on exactly what information was given to the participants of the experiment are presented. However, the research concluded that all-arrow signal faces achieve better responses than a mixture of arrows and circles.

The above mentioned documents are the more relevant references which directly address the interpretation of and research on the effectiveness of red turn arrows. Since the subject research required a "before and after" study of field deployments of the red arrow as well as the standard circular red indication, the authors of this report pursued additional references which provided ideas on field procedures [2,3,6,19,20,23], standard practices [9,10], right-turn-on-red[1], characteristics of turning movements[11], and applications of signals and signal indications [4,12,14,15,16,17].

Based on the relevant documents reviewed, the following observations evolved:

1. There is disagreement in the traffic engineering community on whether the red turn arrow is valuable as a traffic control device.
2. Past research efforts present no convincing argument in favor of nor against the steady red turn arrow indication as a traffic control device suitable for specific applications.
3. The existence of users and non-users among the many jurisdictions of the United States creates a potential safety problem arising out of non-uniformity in practice.
4. Concern for the probable ambiguous meaning of the red turn arrow has been advanced.
5. At least one national study shows that the red turn arrow is not among the least understood traffic control devices.

CURRENT PRACTICES

This section of the report reviews the current practice in the use of red arrow turn signal indications in selected jurisdictions. Viewpoints of traffic engineering officials of a sample of twenty-four non-randomly selected states, cities and counties are presented. The sample involved jurisdictions of eastern, central and western United States, including northern and southern areas. The findings presented are the result of personal and telephone discussions of the status quo of red turn arrow usage among city, state, and county officials in Detroit, Washington, D.C.; Phoenix, Arizona; Long Island, New York; Montgomery County, Maryland; Minnesota; Massachussetts; Delaware; North Carolina; Texas; Ohio; Michigan; Wisconsin; Pennsylvania; Baltimore, Maryland; and Denver, Colorado.

Users of Red Turn Arrow

Detroit, Washington, D.C., Long Island, New York, Massachusetts, Minnesota, Montgomery County, Maryland, Phoenix, Arizona, Wilmington, Delaware, and the state of Delaware are the red arrow users covered in this study. The extent of usage of the red arrow turn signal indication varies among jurisdictions. Tables 1, 2, and 3 indicate the various signal, sign, and mount characteristics. Among the users of the red turn arrow, few jurisdictions -- Washington, D.C. and Delaware -- use it in both left and right turns. Use of the red turn arrow for the left turn is significantly more popular than its use for right turns. Thirty-eight percent -- nine jurisdictions -- were users of the red arrow in one form or the other. Although the sample suggests a 38 percent utilization of red arrows in traffic signals, this should not be interpreted as being representative of the national situation. The authors, however, believes the national percent of users, considering all levels of jurisdictions, is significantly less than 38 percent.

Cited Reasons for Using Red Turn Arrows

Reasons for use of red turn arrows were sought from practicing traffic engineers with the hope that relevant hypotheses would be advanced for field testing. Unfortunately, no new hypotheses evolved from the discussions. However, the cited reasons for the continued use

TABLE 1: Summary of Practice: Red Arrow Indication in Turn Signals

Jurisdictions	Meaning of Red Turn Arrow			Types of Signal Heads			
	Steady		Flashing	Programmable		Standard	
	Stop	[1]NTOR	[2]TAOFRAS	Red Arrow	Red Ball	Red Arrow	Red Ball
Detroit	X	X	NA	†	X	X	X
Washington, D.C.	X	X	X	†	X	X	X
Long Island, N.Y.	X	X	NA	†	X	X	X
Massachusetts	X	X	NA	†	X	X	X
Minnesota	X	X	NA	†	X	X	X
Montgomery Co., M.D.	X	X	NA	†	X	X	X
Phoenix, Ariz.	X	MUTCD	NA	†	X	X	X
Wilmington, Del.	X	X	NA	†	X	X	X
Delaware (State)	X	X	X	X	X	X	X

1. NTOR = No Turn on Red

2. TAOFRAAS = Turn **Allowed on** Flashing Red Arrow After Stop

NA = Not Applicable

X = Yes

† = No

MUTCD = National Manual on Uniform Traffic Control Devices

TABLE 2: Summary of Practice: Red Arrow Indication in Turn Signals (Continued)

Jurisdictions	Arrow Phasing					Exclusive Turn Lanes		Signal Timing Red Arrow Usage	
	Green, Pedestrian Protected	Red							
		Protected		Protected-Permissive					
		RT	LT	RT	LT	Single	Double	Fixed	Traffic Actuated
Detroit, Michigan	X	X*	X	†	†	X	†	X	X
Washington, D.C.	X	X	X	†	†	X	X	X	X
Long Island, N.Y.	X	†	X	†	†	X	†	X	X
[1]Massachusetts	X	NA	X	NA	†	X	†	†	X
Minnesota	X	NA	X	NA	†	X	†	†	X
[1]Montgomery Co, Md.	X	NA	X	NA	†	X	†	†	X
Phoenix, Arizona	X	NA	X	NA	†	X	X	X	X
Wilmington, Del.	X	X	X	†	†	X	X	X	†
Delaware (State)	X	X	X	X	X	X	X	X	X

[1]Red Arrow deployments scheduled for removal

NA = Not Applicable

X = Yes

* = About to stop this practice because of Right Turn on Red.

† = No

RT = Right Turn

LT = Left Turn

TABLE 3: Summary of Practice: Red Arrow Indication in Turn Signals (Continued)

Jurisdictions	Signal Mount			Supplementary Worded Turn Signs									
	Over Lanes	Median	Corner Post	[1]NLTORA	[2]TOGAO	[3]NTOR	[4]TAOFRAAS	[5]NTORA	[6]RTORAS	[7]LTOGAO	[8]LTS	Left	Right
Detroit, Michigan	†	X	X	†	†		NA	†	X	†	†	X	X
Washington, D.C.	†	X	X	†	X	X	†	†	†	†	†	†	†
Long Island, N.Y.	†	†	X	†	†	†	NA	†	NA	X	†	†	†
Massachusetts	X	X	X	†	†	†	NA	†	NA	X	X	†	†
Minnesota	X	X	X	X	†	X	NA	X	X	†	†	†	†
Montgomery Co, Md.	X	†	†	†	†	†	NA	†	†	†	†	†	†
Phoenix, Arizona	X	†	X	†	†	†	NA	NA	†	X	X	†	†
Wilmington, Del.	X	†	X	†	†	†	NA	†	†	†	†	†	†
Delaware (State)	X	†	†	†	†	†	X	†	†	†	†	†	†

1. NLTORA = No Left Turn On Red Arrow
2. TOGAO = Turn On Green Arrow Only
3. NTOR = No Turn On Red
4. TAOFRAAS = Turn Allowed On Flashing Red Arrow After Stop
5. NTORA = No Turn On Red Arrow
6. RTORAS = Right Turn On Red After Stop
7. LTOGAO = Left Turn On Green Arrow Only
8. LTS = Left Turn Signal

X = Yes
† = Not Used
NA = Not Applicable

of red turn arrows may be of interest to traffic engineers and are listed as follows:

- Red arrows have been legally adopted in the local vehicle codes and are legitimate within the jurisdiction.
- Red arrows have been adopted into the National Manual on Uniform Traffic Control Devices (MUTCD) which is totally adopted by the jurisdiction.
- In part, the recommended use of red turn arrows in the National MUTCD has been adopted. Demonstrated satisfaction has been observed through other applications not mentioned in the MUTCD.
- Compared with optically programmable heads, use of standard signal heads with red arrows has a significant cost-benefit advantage.
- There is a strong belief, based on field observation, that most motorists understand the meaning of red turn arrows.

The last reason touches on the safety significance of red turn arrows. While the traffic engineers who use red turn arrows are quite sure of the benefits of each field application, limited rigorous assessment of safety has been conducted. Washington, D.C. is confident that the red turn arrow has no disadvantage over the circular red indication. Two studies[5][13] appear to be the basis for this confidence. Massachusetts believes that its policy in providing leaflets for informing motorists, during drivers' license renewal, of new traffic control devices has been effective. The red turn arrow was the subject of one of these notices. In one other jurisdiction, Delaware, the use of red turn arrows for more than 15 years is believed to be the basis for an apparently high level of compliance.

Experience in Using Red Turn Arrows

Long Island City, New York: Red left turn arrows are deployed at two intersections in Long Island City. Separate phasing for vehicles and pedestrians are provided. The signal heads with the red turn arrow are separate from those for the through movement and are post mounted. A signed message, "left turn on green arrow only", supplements the display of the red arrow. Traffic engineering officials are not aware of any

unsafe conditions resulting from the deployed red arrows. No warrants have specifically addressed the use of red arrows.

Detroit, Michigan: The city of Detroit, Michigan, uses an abundance of red turn arrows for both left and right-turns. Where pedestrian activity is significant, separate pedestrian phasing is provided. Signed messages prohibiting turning during the red arrow display are deployed in some locations. Most of the red arrow deployments are post mounted. The city claims that there are no unusual safety nor congestion problems resulting from the red arrow. Red arrow applications in Detroit are primarily based on the recommendations of the National MUTCD. The use of red turn arrows is popular at intersections with multi-phase control. The right-turn-on-red rule has recently caused officials to limit and reduce the usage of the red arrow for the right turn, since the city feels that no movement should be allowed during the red turn arrow.

Phoenix, Arizona: This city reported limited use of the red arrow for left turns only. It is believed that the right turn red arrow has potential for encouraging illegal right turns during its display. It is illegal to use the red turn arrow for right turns in Phoenix. A signed message, "turn on green arrow only" emphasizes that motorists are not to turn during the display of the red left turn indication. The city reports no unusual safety problems resulting from use of the red left turn arrow. Both post and overhead signal mounts are utilized. Pedestrians receive exclusive phasing.

Wilmington, Delaware: Wilmington has been using red turn arrows for more than 15 years. Traditionally, red arrows were used purely to emphasize the need for vehicles to stop and not turn during the pedestrian walk phase. The traditional meaning of the red turn arrow is transferred to recent applications where vehicles are not allowed to turn during the display of the red arrow. Red arrows are used in multi-phase controls with fully protected turning movements. Where pedestrian activity is high, such as in the central business district, exclusive pedestrian phasing is provided. Several single and double turn lanes have received treatment of red left and right turn arrows. Corner post and mast-arm

mounts are common supports for the traffic signals. City traffic engineers claim that the red turn arrow poses no safety hazard. No signs are used to supplement the red turn arrow.

Montgomery County, Maryland: This county uses the red arrow for left turn lane control at two locations. By choice, the county has avoided the use of the red arrow indication for right turns. The RTOR rule is said to be in conflict with the red turn arrow. The two locations at which left turn red arrows are used have been recently scheduled for a new signalization design involving permissive left turns during the through green. The county states that this change is in the interest of energy conservation, and not because of any known problems associated with the red arrows. Overhead signal mounts are used at the two previously mentioned locations. Exclusive pedestrian phasing is used only in two locations. As a policy, the pedestrian walk phase is designed to be in no conflict with arrow-controlled turn movements. No signs are used with red turn arrows.

State of Delaware: Delaware uses both right and left red turn arrows in traffic signals at many intersections along state administered facilities. Red arrow usage for right turns is less common than that for left turns. All the signals are supported on span-wire mounts and are situated over the lanes which they are intended to control. Leading left turn phasing is a common practice. Where pedestrian activity is significant, pedestrian signals with separate phasing are provided, such that there is no conflict with the green arrow.

A peculiar characteristic of the state arterials where many red turn arrows are used is the very wide median. The exit sections of some left turn lanes on the divided arterials make an acute angle with the through lanes, such that it is difficult for drivers in the turn lanes to view the through signals. Figure 9 in the Appendix demonstrates these features. The channelization for left turn in some cases involves curved single and double turn lanes along with a traffic island on the right hand side. With this angled orientation of the turn lanes, opposing turning vehicles are not aimed into the nose of the opposite median nor into the

opposing turning traffic. This uncommon channelization requires that the turn signals be located remotely away from those of the through movement. The red arrow is used to emphasize the left or right turn in this geometrical situation. No signs are used to accent the need for vehicles to stop and remain standing throughout the display of the steady red turn arrow.

At some intersections along arterials, permissive turns are allowed by flashing the red arrow. In such cases, the signal displays the circular red indication before the flashing red arrow, and returns to the circular red before displaying the green indication.

The steady red right turn arrow is also used to emphasize the need for motorists' to remain in a stopped position and not turn right during the pedestrian walk phase. If the walk signal is not actuated by a pedestrian, vehicles are allowed to make a right turn on red during the display of the circular red indication. As a policy, Delaware intends to minimize the use of signs to accent the meaning of signal indications. Permissive turns during the flashing red arrow are indicated by a sign carrying the message "turn on flashing red permitted after stop".

Washington, D.C.: This city demonstrates an abundance of deployments of red turn arrows in traffic signals. Red arrows are used for left and right turns. Wherever red arrows are used, vehicles are required to stop and not move before the arrival of the green indication. Two signs are common with red turn arrow applications--"no turn on red" and "turn on green arrow only". These signs, as well as the signals, are post mounted. The signal heads with arrows are generally separated from those with the circular indications, even though heads with circular and arrow indications may be mounted on the same post. Both corner and median posts are used. Field applications include "Y", "T", and "X" intersections as well as unusual channelizations such as Dupont Circle. The red turn arrow, although post mounted, is intended to control exclusive turn lanes. Flashing the red left turn arrow allows a turn with caution after stop.

The District uses the recommendations of the MUTCD regarding pedes-

trian phasing. Wherever green arrows are used, no conflict is allowed between turning vehicles and crossing pedestrians. During the display of the green turn arrow, the pedestrian "don't walk" signal is active, controlling the cross-street into which a vehicle may be about to turn.

State of Minnesota: The traffic engineering officials of Minnesota conducted field studies to evaluate potential safety problems which would have resulted in their use of red arrows in traffic signals. In August of 1978, traffic violations were observed at three intersections during a "before and after" study. The circular red indication used in the left turn signals was replaced by the red left turn arrow during the "after" study. The results of the study showed no evidence of safety differences between the red arrow and the circular red indications.

In another attempt to establish safety differences between the red arrow and the circular red indication, Minnesota DOT conducted another study in July 1979. Nine locations -- five equipped with red left turn arrows and four with the circular red indication -- were studied. Violations and stopping characteristics -- normal and erratic -- were observed for approximately one month. Based on the statistical analysis of the collected data, Minnesota DOT concluded that there is little practical difference in motorists' responses to the two different shapes of red left turn indications. All the locations with the circular red indication were controlled with programmable heads. No left-turn-on-red arrow signs were used at the locations with the red arrow.

Minnesota continues to use the red arrow for left turn only. In this application vehicles are required to stop and not enter the intersection. Red turn arrows are applied principally to protected left turn movements at multi-phase intersections along divided highways administered by the state. Median post and mast-arm mounts are used. Where green arrows are used, pedestrian movements are phased such that they are not in conflict with turning traffic. Since the right turn on red arrow is not used it is not in conflict with the RTOR policy.

State of Massachusetts: Massachusetts is one of the few jurisdictions which attempted to educate its motoring public about the meaning

of the red turn arrow. This has been accomplished through leaflets given to drivers during the renewal of their licenses. Drivers facing a red left turn arrow are expected to stop and not turn before the appearance of the green indication. All usages of the red left turn arrow are limited to fully protected left turns.

The red left turn arrow is used on a limited basis, involving few intersections. Yet, traffic engineering officials are concerned as to whether the red arrow usage at the few intersections should remain as they are. Since the National MUTCD does not allow flashing of the red turn arrow to permit a protected-permissive turn, the officials are considering removal of all their red turn arrow installations.

While the officials have not studied the merits of the red arrow, there is some concern about its possible limited target value and the effect of same on the elderly community. The Department of Public Works reported that two fatal accidents occurred at intersections where red arrows are used. Both accidents occurred in locations where elderly persons reside. While it is not certain that the red arrow was responsible in any way, the accidents have raised questions on the effectiveness of the red arrow. Arrow mounts include the mast-arm, span-wire, and post.

Non-Users of Red Turn Arrows

The experience of traffic engineering officials of jurisdictions which do not use red arrows has value in presenting major concerns which discourage the use of red turn arrows. Knowledge of these concerns should be of interest since most jurisdictions do not use red turn arrows and may have valid reasons for adopting this opposition. Further, the viewpoints against the use of red turn arrows can be the basis for identifying some hypotheses which can be tested in evaluating the relative safety merits of red and circular arrow indications used in traffic signals.

Reasons Cited for Not Using Red Turn Arrows

The reasons for not using red turn arrows are based on telephone discussions with traffic engineering officials of 16 jurisdictions across

the United States. These include: Westchester County, New York; North Carolina; Cincinnati, Akron and Cleveland of Ohio; Wayne County and Lansing of Michigan; California; Wisconsin; Pennsylvania; Pittsburgh, Pennsylvania; Washington; Colorado; Denver, Colorado; Texas; and Baltimore, Maryland. The jurisdictional levels include states, counties and cities.

From the views expressed by the officials the more popular anti-red arrow comments are the following:

1. The red arrow is inherently a confusing and complicated indication. It is felt that the arrow would always be associated with motion and that the red color confounds the message transmitted by the shape of the arrow. Moreover, some supporters of this position are so convinced of its correctness that research to shed more light on the matter is deemed unnecessary.
2. The red arrow has inadequate target value.
3. Use of the red arrow would require the addition of new signs wherever they are used. This is viewed as a necessary safety measure to supplement the message of the arrow.

The above reasons are directly related to safety. No prudent traffic engineer should knowingly deploy devices which suffer from reasons #1 and #2. Reason #3 ties into a growing feeling among practitioners that there is need to minimize the amount of devices used today since motorists are already confronted with too many traffic control devices. Moreover, the addition of a sign to supplement the message of a new signal indication has raised concerns about the real merits of the signal indication. Non-adoption of red arrow usage into the local vehicle code and the local equivalent to the MUTCD are other cited reasons for not using red turn arrows. Reasons #1 and #3 will be addressed in this report. Reason #2 does not fall within the scope of this research, but is an area worthy of investigation. At least one jurisdiction which uses red turn arrows -- Delaware -- has increased the size and changed the shape of one of its red turn arrow deployments to increase its target value.

Characteristics of Red Arrow Applications

The general findings regarding the use of the circular and red arrow indications are summarized in Tables 1 through 3. Most of the jurisdictions studied welcome the use of the red arrow for allowing turns during its display. There is a common understanding of the meaning of the steady red arrow. All the jurisdictions have adopted the stop-and-wait-for-green meaning as the standard practice, even though some of these jurisdictions have stated that the national MUTCD is their official manual. Significant use of the red turn arrow for the right turn was observed only in Washington, D.C. and Delaware. Some jurisdictions -- Detroit and Massachusetts -- have initiated the removal of all red arrow applications for the right turn. Possible conflicts with the right-turn-on-red rule have been cited as the principal reason.

Only Washington, D.C. and the State of Delaware reported the practice of flashing the red arrow. In this application the arrow has the meaning of stop, then proceed to make a left or right turn with caution. In Washington, D.C. the flashing red arrow receives principally urban applications in which the signal heads are post mounted on the median or at the corners of the intersection. In Delaware, the mounts are span-wire and the signal heads are located over the lanes and are supplemented by a sign which alerts the motorists to the meaning of the flashing red arrow. No signs are used in Washington, D.C. to supplement the flashing red arrow.

All the jurisdictions use programmable and standard signal heads for traffic control at intersections. However, programmable heads tend to be reserved for intersection approaches where there is a strong likelyhood of motorists responding to the wrong signal. In only one jurisdiction, Delaware, the red arrow was used in a programmable head directed at the stem approach into a "Y" intersection. This arrow was not the standard type; it had been widened to increase its target value.

The officials were not quite sure of the operating characteristics of every field deployment of pedestrian signals, but indicated a common policy, based on the National MUTCD, of protected phasing of traffic

controlled by green arrows such that there is no conflict with other vehicles and pedestrian movements.

Protected phasing of turning movements is the practice for jurisdictions which use red turn arrows. Only Delaware has the unusual practice of a combined usage of the steady and flashing red indications to allow protected-permissive turns on some of its busy arterials. There it is felt that flashing the red arrow in sequence to the steady arrow brings the motorists to a complete stop before turning, as opposed to the turn-on-green-with-caution which does not require motorists to stop. Delaware's officials believe that there is a safety advantage of requiring motorists to stop at some high-volume intersections where a permissive turn on the through green is not a safe move throughout the day.

Red arrow applications involved both single and double turn lanes in central areas of cities as well as in suburbia or rural towns. Fixed-time controls predominate in the high density urban areas. Suburban arterials administered by the state and the counties receive more frequent treatments of traffic actuated systems where the signal timing is variable.

Eight different types of worded messages were observed in use with red turn arrows. No single jurisdiction uses all the signs indicated in Table 3. The "Left Turn Signal" sign is more common, appearing in three jurisdictions. An abridgement of the message, "Left Turn Signal", in the form of a "Left" sign is used in Detroit. A "Right" sign is also used in Detroit in some locations where right turns are controlled by turn signals. It should be observed that Delaware uses very few signs, even though it deploys an unusual sign indicating that a turn is allowed during a flashing red arrow. Washington, D.C. has the highest density of red arrows for both left and right turns, and is the most urbanized of the studied jurisdictions. In that city "No Turn On Red" and "Turn On Green Arrow Only" are common signs found in association with signal heads where red arrows are used for the right turn.

CHAPTER IV
FIELD STUDIES

Study Design

The field studies involved the identification of a set of measures for evaluating equivalent turn-applications of red arrow and circular red indications, the selection of field sites from intersections made available by several jurisdictions, the collection of the data, and a statistical analysis.

Measures

After carefully examining an exhaustive set of safety-related measures of effectiveness, it was determined that accident-prone conflicting maneuvers of turning and through vehicles and the proportion of cycles with turn violations during the red indication are the basic measures. The definition of a violation in this research is limited to the act of drivers entering and clearing the intersection during the red indication. It excludes violations of the red indication due to "stretching the amber" and any form of obstructed vehicle movement at the intersection. The proportion of violated cycles is expressed as a violation ratio which is equal to the number of cycles with red violations divided by the number of cycles with red-violation opportunities.

Hypotheses

An exhaustive list of hypotheses were developed. However, it was recognized early in the research that some hypotheses may have to be deferred if sufficient data for a meaningful statistical analysis were unavailable. This is due to the fact that some jurisdictions will not allow the study team to deviate too much from their standard practices, and that practices vary among jurisdictions. The key hypotheses focused on whether there is any statistically significant difference in the violation ratios during the two shapes of the red indication at "cross", "T", and "Y" intersections, and whether the ratios are affected by such items as the type of signal mount, time of day, turn signs, and the prior experience of the jurisdiction in using red arrows in turn signals.

Field Sites

Field observations were conducted at fifteen intersection approaches located in five jurisdictions which were willing to assist in this study. The primary intersection selection criteria were current practices of red turn arrow usage, desire of officials to faciltate the field work, type of intersection, signal mount, type of turn, right-turn on red utilization and supplementary signs. Table 4 presents the study sites by location and general characteristics. Further detail on intersection approach geometrics, type of signalization and signing can be found in the Appendix.

Three intersections were selected in Westchester County, New York, one in the District of Columbia, six in Delaware, two in Minnesota, and three in Colorado, in order to contrast and compare conflict rates and violation ratios between users and non-users of the red turn arrow indication in different geographical settings. Colorado, Delaware, Minnesota, and Washington, D.C. are among the jurisdictions with strong feelings about the positive value of the red turn arrow as a safe traffic control device, and have experimented with it to varying degrees. In Delaware, red turn arrows have been in use for many years with an apparently high level of compliance. In Washington, D.C., an abundance of deployments of red turn arrows have been demonstrated. Both Delaware and Washington, D.C. are among the few jurisdictions that use the red arrow for both left and right-turns. Minnesota has a very limited experience in using red turn arrows. Colorado and Westchester County, New York are non-users and are to be compared with the more experienced jurisdictions.

Data Collection

Data collection was performed over the period of February to May, 1981. Violations, conflicts, cycles, volume, and time of day were observed at each intersection approach during the "before" condition (existing red turn signal indication) and the "after" condition (red turn indication changed to "ball" or arrow, which ever is appropriate). The "after" data collection was performed approximately four weeks following the signal indication modifications. Each intersection approach was

TABLE 4. General Characteristics of the Selected Study Sites

Site #	Turn	Intersection Type	Mount	Control	Shape of Indication		Sign	Jurisdiction
					Green	Red		
1	LT	T	OH	Full	A	B	LLMTL	N.Y.
2	LT	C	OH	Semi	A	B	--	N.Y.
3	LT	C	OH	Semi	A	B	--	N.Y.
7	RT	T	CP	Fixed	A	B	NTOR	D.C.
10	LT	T	OH	Full	A	B	--	DEL.
11	LT	T	OH	Full	A	B	LTOGAO	DEL.
15	LT	C	OH	Full	A	A	--	DEL.
16	LT	C	OH	Full	A	A	--	DEL.
19	LT	Y	CP	Full	A	A	--	DEL.
20	LT	Y	OH	Full	A	A	NTOR	DEL.
26	LT	C	MP	Full	A	B	LTS	MIN.
27	LT	C	MP	Full	A	B	LTS	MIN.
32	LT	C	MP	Full	A	B	LTOAO	COL.
35	LT	C	MP	Full	A	B	LTOAO	COL.
36	LT	T	MP	Full	A	B	LTOAO	COL.

LT - Left Turn
RT - Right Turn
C - Cross
T - T-Intersection
Y - Y-Intersection

OH - Overhead Mount
MP - Median Post Mount
CP - Corner Post Mount
Full - Fully Actuated
Semi - Semi Actuated
Fixed - Pre-Timed

A - Arrow
B - Circular (Ball) Shape
NTOR - No Right Turn on Red
LTOGAO - Left Turn on Green Arrow Only
LTS - Left Turn Signal
LLMTL - Left Lane Must Turn Left

studied for two days by a team of the same two trained observers during the morning and afternoon peaks, day-time off-peak, and night-time and off-peak periods for both the "before" and "after" conditions. Data collection occurred only in good weather driving conditions. No data was collected during periods of icy roads, fog, rain, or snow.

The Experiment

In preparation for the statistical analysis, the data was organized in sets of observation periods discussed earlier. Conflicts resulting from the shape of the red was observed to be extremely rare, and thus conflict rates were eliminated from further consideration.

The analysis considered the effect of a number of experimental factors on the violation ratio. Each factor is described by specific attributes and levels as the following:

Factor	Subscript	Identifier	Levels
1. Indication	r	R	1. Red Ball 2. Red Arrow
2. Intersection	i	I	1. "T" 2. Cross 3. "Y"
3. Location	l	L	1. New York and Colorado 2. All other jurisdictions
4. Traffic	t	T	1. a.m. and p.m. peak 2. a.m. and p.m. off-peak 3. Night

5.	Mount	m	M	1. Overhead 2. Post
6.	Sign	s	S	1. Yes 2. No
7.	Violation	v	V	1. Yes 2. No

The abstract view of the experiment is a multi-dimensional contingency table with response variable set to the violation factor. The odds ratio of violations to non-violations is fitted using the log-linear model of Information Theory in the Analysis of Variance framework. The general log odds model takes the form:

$$\text{Log}\left[\frac{P_{r,i,l,t,m,s,1}}{P_{r,i,l,t,m,s,2}}\right] = B^{V} + B_{r}^{VR} + B_{i}^{VI} + B_{l}^{L} + B_{t}^{VT} + B_{m}^{VM} + B_{s}^{VS} + B_{ri}^{VRI}$$

Where P_1 represents the probability of a violated cycle, and P_2 represents the probability of no violation.

The Contingency Table model is a 2 x 3 x 2 x 3 x 2 x 2 x 2 containing 288 cells. An effort was made to collect data for all 288 cells. However, experimental settings provided by the 15 selected sites did not generate data to fill all the cells. Only 43.75% of the cells contain data. Actually, data cells occur in pairs (violations, non-violations), so that 63 of the possible 144 violation ratios could be computed from the data. No "Y" intersections were available in New York and Colorado. Further, the fact that the field team was not given local authorization to remove turn signs is reflected in the data. For example, post mounts involved signs in all locations, and signs occurred in all the Colorado and New York sites. Because of these conditions, the sign factor is ignored.

Data Analysis

The analysis used the light cycle as the basis for the experimental unit. For each light cycle, either no violations occurred, or one or more violations occurred. Thus, for each setting of the experimental factors, the violation factor counts the number of cycles in which at least one violation occurred on the first level, and the number of cycles in which no violations occurred on the second level. All cycles in which there were no vehicles in the study lanes during the red are eliminated from consideration in this analysis.

Westchester County, New York and Colorado

Because Westchester County, New York and Colorado had no prior experience in red arrow usage, they were grouped for analysis and are examined first.

For completeness, the standard model that the response variable (violated cycles) was not affected by any of the independent factors (shape of red, intersection type, time of day, signal mount) was tested. As expected, the model gave a poor fit to the data, and generated an information statistic (2nI) of 67.8 with 23 degrees of freedom (d.f).

In the process of searching for a good fitting model, a straight log-linear model in the independent factors was considered. Such a model involves the first order interactions of the violation factor with each of the independent factors, i.e., the model requires knowledge of the following marginal totals:

Violation	-- Shape of red light	(R)
Violation	-- Type of intersection	(I)
Violation	-- Time of day	(T)
Violation	-- Signal mount	(M)

This model was an improvement ($2nI = 34.0$, $d.f. = 18$, and probability $P = 0.01$), but clearly not good enough. Second order interactions were necessary. The selected model was:

Violation -- Shape of red light (R)
Violation -- Intersection type - time of day
Violation -- Time of Day - Mount

The fit for this model was good as indicated by 2nI = 12.3, d.f. = 14, and P = 0.58.

The effect of dropping any of the interactions down one level produces the following results.

Factor Dropped	2nI	d.f.	P.
Violation-Shape of Red	7.5	1	0.006
Violation-Intersection-Time of Day	7.5	2	0.02
Violation-Time of day-Signal Mount	14.3	2	0.01

The results suggest that each term is necessary for a good fit. Table 5 shows the violation ratios for each of the required marginal totals. The violation ratios for red arrow (0.065) is signficantly below that for the red ball (0.082). There are no higher-order interactions involving the shape of the red indication, so the result is clearer. The time of day factor shows a higher violation ratio for peak periods, but other results are less definitive. In particular, the night violation ratio for cross intersections (0.042) is quite low. A comparison of the red arrow and the red ball for different experimental settings is presented in Table 6. Considering differences in violation ratios greater than 0.01, the table clearly shows that in seven settings the red arrow was better, in three it made no difference, and the red ball was better in only two settings.

Other Locations

Other locations include sites in Delaware, Minnesota, and Washington, D.C. As you may recall, these jurisdictions had experience in using red arrows.

Because there were no post-mounted signals at the "Y" intersections of the selected sites, the analysis was performed with the mount factor deleted. These data were difficult to fit. A good model seemed to require all second-order interactions involving the violation factor:

TABLE 5. Violation Ratios for New York and Colorado Sites

Factor		Violation Ratio*
1. Red:		
Arrow		0.065
Ball		0.082
2. Intersection Type:		
"T"		0.080
Cross		0.071
3. Time of Day:		
Peak, a.m. and p.m.		0.088
Off-Peak, Day		0.063
Night		0.053
4. Mount:		
Overhead		0.077
Post		0.071
5. Intersection Type and Time of Day:		
T:	Peak, a.m. and p.m.	0.092
	Off-Peak, Day	0.057
	Night	0.078
Cross:	Peak, a.m. and p.m.	0.086
	Off-Peak, Day	0.067
	Night	0.042
6. Mount and Time of Day:		
Overhead:	Peak, a.m. and p.m.	0.101
	Off-Peak, Day	0.048
	Night	0.050
Post:	Peak, a.m. and p.m.	0.075
	Off-Peak, Day	0.077
	Night	0.056

*Cycles with red violation divided by the number of cycles with red violation opportunities.

TABLE 6. Comparison of Violation Ratios.
New York and Colorado

Experimental Setting Pairs		CYCLES			Violation Ratio
		Violated	Non-Violated	Total	
1.	TROA	30	265	295	0.102
	TROB	32	265	297	0.108
2.	TRPA	21	289	310	0.068
	TRPB	28	278	306	0.092
3.	TDOA	3	141	144	0.021
	TDOB	8	125	133	0.060
4.	TDPA	12	149	161	0.075
	TDPB	11	149	160	0.069
5.	TNOA	10	127	137	0.073*
	TNOB	6	95	101	0.059*
6.	TNPA	11	113	124	0.089
	TNPB	12	129	141	0.085
7.	CROA	56	573	629	0.089
	CROB	74	614	688	0.107
8.	CRPA	29	512	541	0.054
	CRPB	49	498	547	0.090
9.	CDOA	11	255	266	0.041
	CDOB	20	315	335	0.060
10.	CDPA	28	291	319	0.088*
	CDPB	22	290	312	0.071*
11.	CNOA	7	220	227	0.031
	CNOB	14	257	271	0.052
12.	CNPA	6	264	270	0.022
	CNPB	18	283	301	0.060
TOTAL		518	6,497	7,015	

T = T intersection
C = Cross intersection
R = Peak Period, Day
O = Overhead Signal Mount
Y = Y intersection

D = Off-peak, Day
N = Night-time
A = Red Arrow
B = Red Ball
P = Post Mounted Signal

Arrow equal or better than the red ball in all pairs except #5 and #10.

Violation -- Shape of red - Intersection type
Violation -- Shape of red - Time of day
Violation -- Intersection type - Time of day

The model having violations not affected by the independent factors had $2nI = 123.6$, d.f. = 17, $P = 0$. The linearity model had $2nI = 30.5$, d.f. = 12, and $P = 0.0023$. The second-order interaction model above had $2nI = 4.5$, d.f. = 4, and $P = 0.34$. Thus, many parameters must be estimated for this model. The violation ratios for the required marginal totals are given in Table 7.

As you may recall, Delaware, District of Columbia, and Minnesota had prior experience in using red arrows. Yet, Table 7 clearly shows that less violations occurred with the red arrow, although the difference is not as great as that for jurisdictions with no prior experience. In addition, it is clear that the red arrow experiences significantly less violations at night and at "T" intersections. Table 8 shows the comparison of the individual settings. Considering differences in violation ratios greater than 0.01, Table 8 demonstrates, for the other locations, that there are six settings in which the arrow was better, two in which the ball was better, and one tie.

TABLE 7. Violation Ratios for Sites in Delaware District of Columbia, and Minnesota

Factor		Violation Ratio
1. Red:		
Arrow		0.057
Ball		0.067
2. Shape of Red and Time of Day:		
Red Arrow:	Peak, a.m. and p.m.	0.068
	Off-Peak. Day	0.047
	Night	0.047
Red Ball:	Peak	0.067
	Off-Peak, Day	0.056
	Night	0.080
3. Shape of Red and Intersection Type:		
Red Arrow:	T	0.056
	Cross	0.037
	Y	0.091
Red Ball:	T	0.081
	Cross	0.039
	Y	0.092
4. Intersection Type and Time of Day:		
T:	Peak, a.m. and p.m.	0.071
	Off-Peak, Day	0.049
	Night	0.083
Cross:	Peak, a.m. and p.m.	0.039
	Off-Peak, Day	0.038
	Night	0.034
Y:	Peak, a.m. and p.m.	0.108
	Off-Peak, Day	0.084
	Night	0.067

TABLE 8. Comparison of Violation Ratios.
Minnesota, Delaware, and District of Columbia

Experimental Setting Pairs		CYCLES			Violation Ratio
		Violated	Non-Violated	Total	
1.	TRA	67	955	1022	0.066
	TRB	72	872	944	0.076
2.	TDA	20	562	582	0.034
	TDB	37	551	588	0.062
3.	TNA	37	582	619	0.060
	TNB	64	531	595	0.108
4.	CRA	33	861	894	0.037
	CRB	39	901	940	0.041
5.	CDA	26	567	593	0.044*
	CDB	20	595	615	0.033*
6.	CNA	14	484	498	0.028
	CNB	19	442	461	0.041
7.	YRA	68	494	562	0.121*
	YRB	53	507	560	0.095*
8.	YDA	25	297	322	0.078
	YDB	27	268	295	0.092
9.	YNA	16	294	310	0.052
	YNB	21	218	239	0.088
TOTAL		658	9,981	10,639	

See Table 6 gor code descriptions.

The red arrow is equal or better than the red ball in all pairs except #5 and #7

CHAPTER V
CONCLUSIONS

Effectiveness of the Left Turn Arrow

The primary objective of this study is to determine if the use of the red left turn arrow indication is an unsafe traffic control device as compared with the circular red indication used for the same purpose.

A sample of professional opinion had suggested the possibility that the red arrow could be confusing in that motorists may interpret the red arrow to mean that they can proceed after stopping. This research effort shows no evidence that such a problem exists with the red arrow when used for the left turn movement. It should be noted, however, that supplementary signs such as "Turn Left on Green Arrow Only" were used at some of the intersections where the red arrows were used. Findings are summarized below:

1. For Westchester County, New York, and Colorado which had no prior red arrow experience, the violation rates (running the red) were 6.5 and 8.2 percent for the red arrow and red ball, respectively. This difference is statistically significant at the 1 percent level.

2. For Delaware, Minnesota, and the District of Columbia which had prior red arrow experience, the violation rates are 5.7 and 6.7 percent for the red arrow and red ball, respectively. This difference is statistically significant at the 5 percent level.

3. For those jurisdictions with prior red arrow experience, the violation rates at tee intersections are 5.6 and 8.1; nighttime violation rates are 4.7 and 8.0 percent for the red arrow and red ball, respectively. The differences in rates for both situations (tee intersections and nighttime traffic conditions) are statistically significant at the 5 percent level.

It is worthy to note that the supplementary signed messages installed with the red indication may be a contributing factor to drivers' understanding of the red arrow. Since the research team was not authorized to remove these signs, the need for these supplementary messages was not analyzed.

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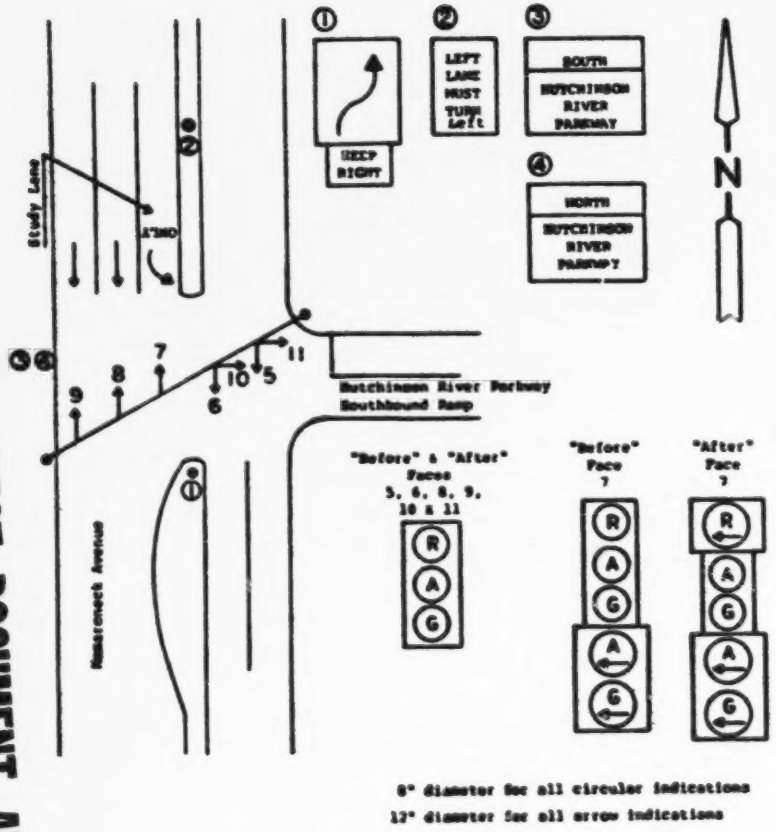

FIGURE 1: Field Site Number 1
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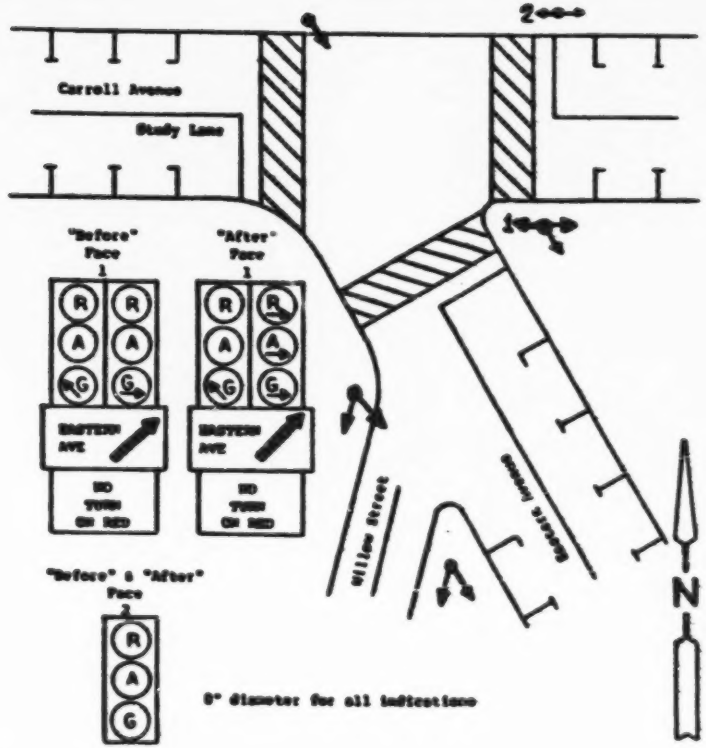

FIGURE 2: Field Site Number 7
Washington, D.C.

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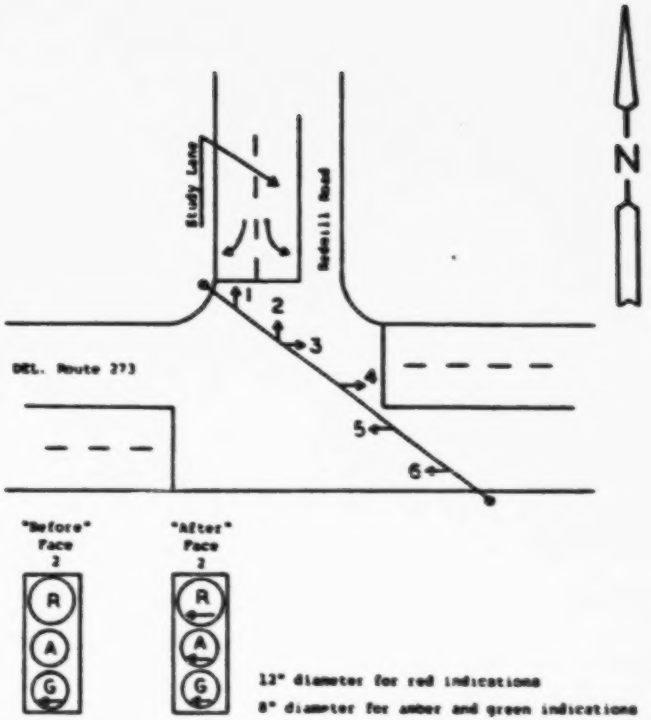

FIGURE 3: Field Site Number 10
Newark, Delaware

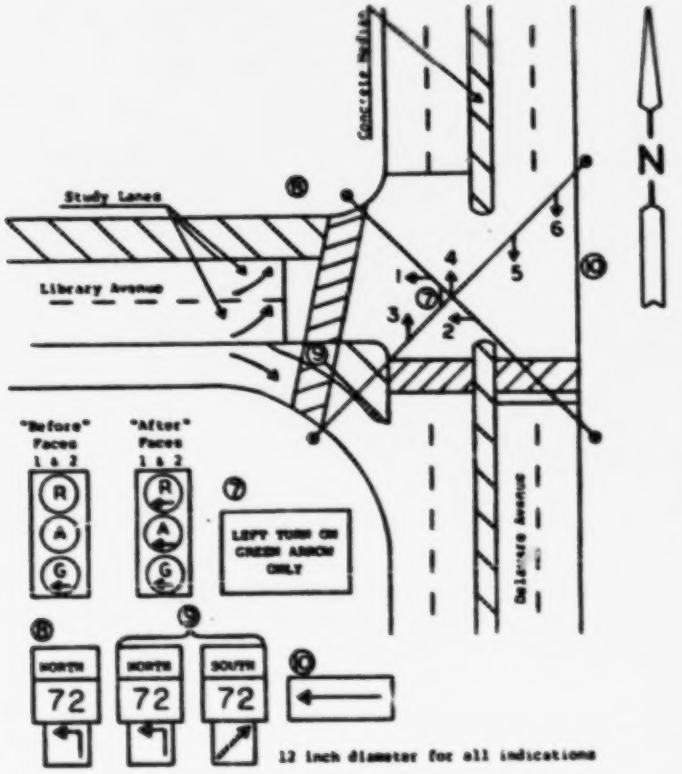

FIGURE 4: Field Site Number 11
Newark, Delaware

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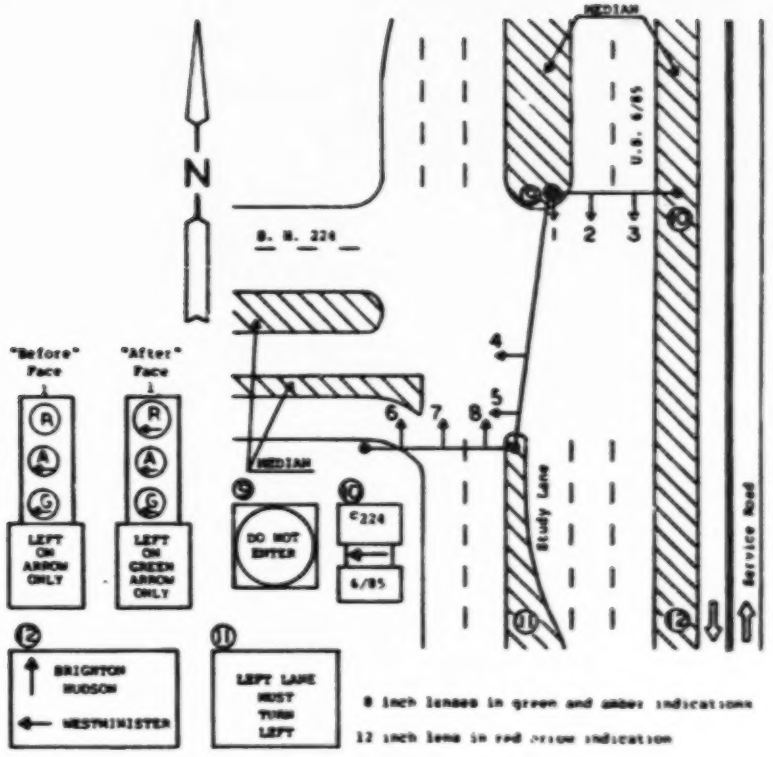

FIGURE 5: Field Site Number 36
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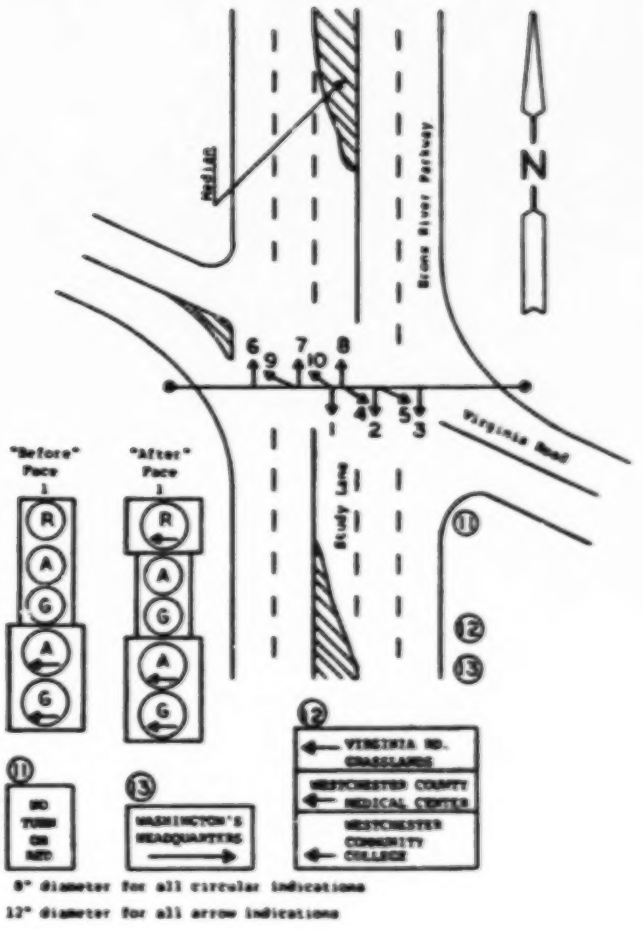

FIGURE 6: Field Site Number 2
Greenburg, New York

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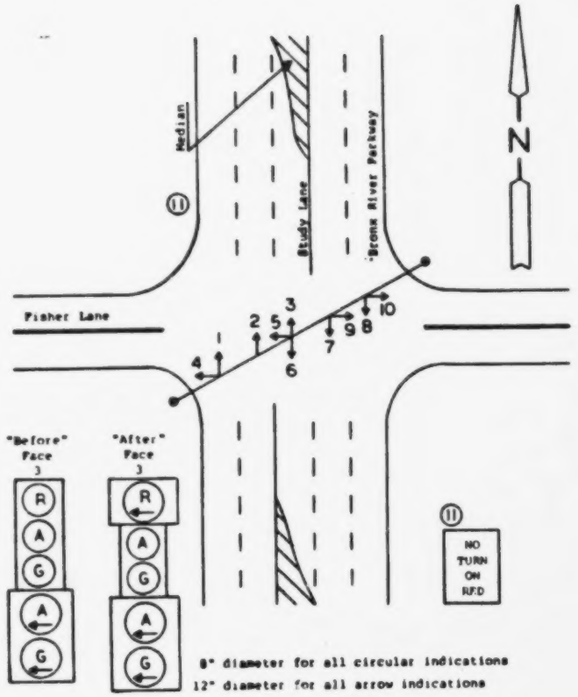

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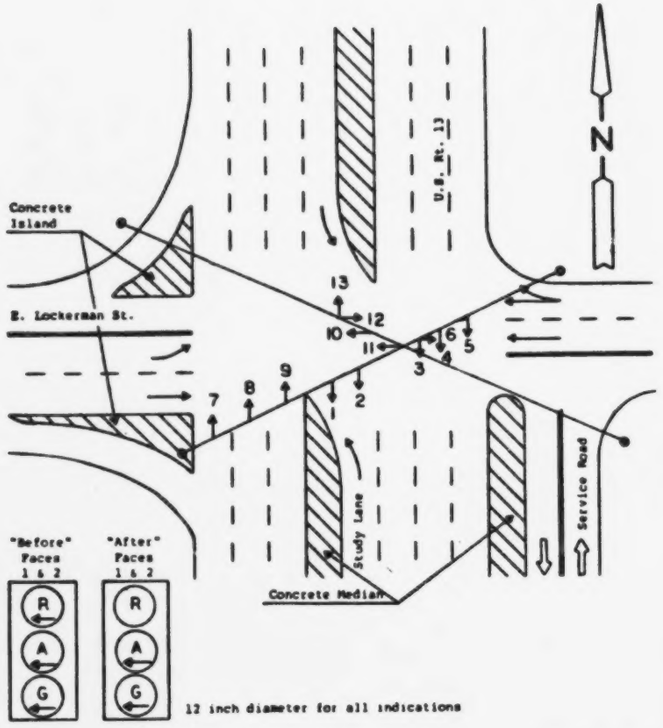

FIGURE 8: Field Site Number 15
Dover, Delaware

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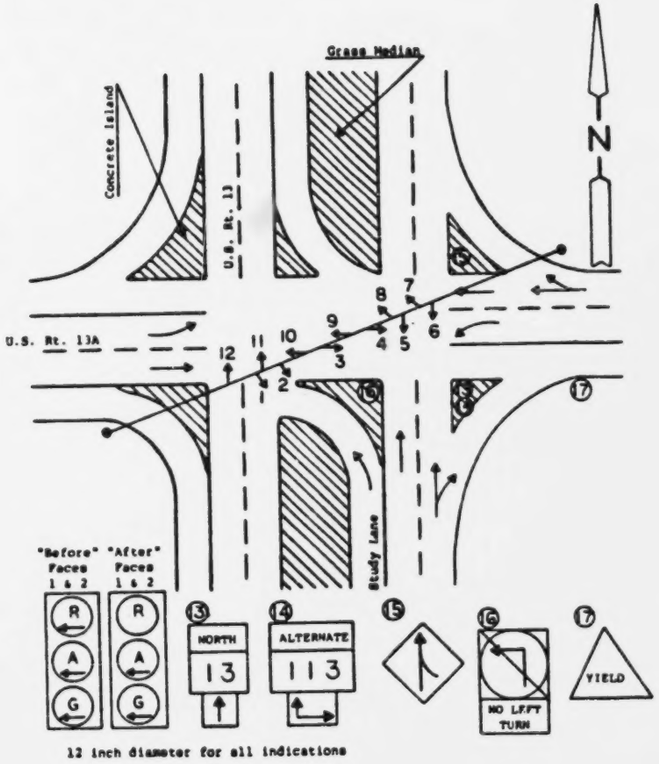

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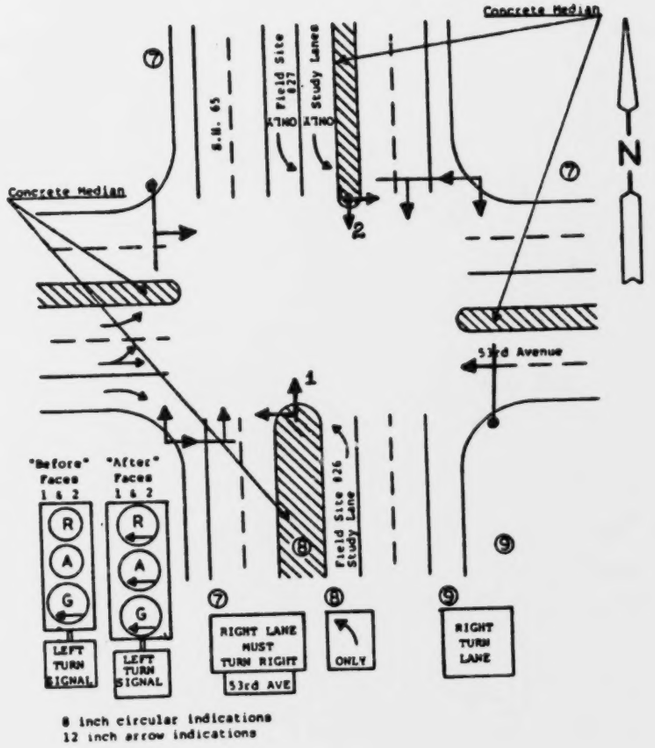

FIGURE 10: Field Sites Number 26 and 27
Columbia Heights, Minnesota

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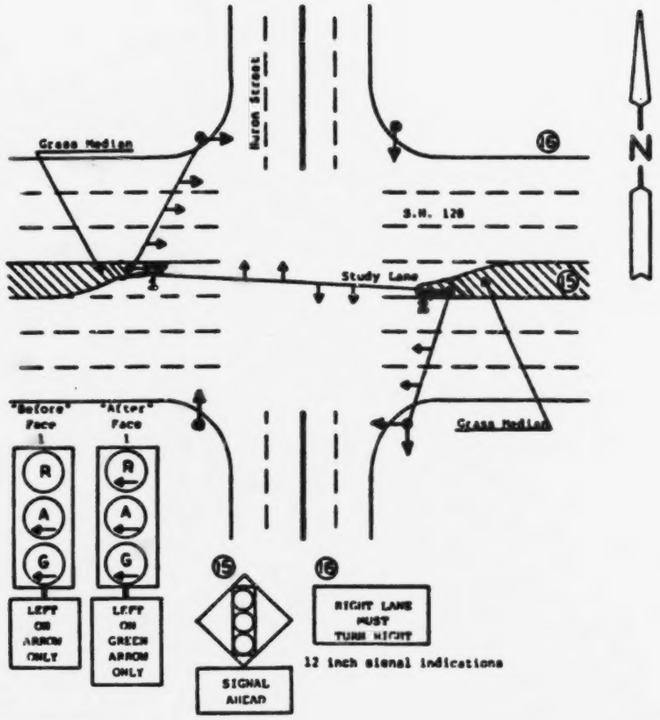

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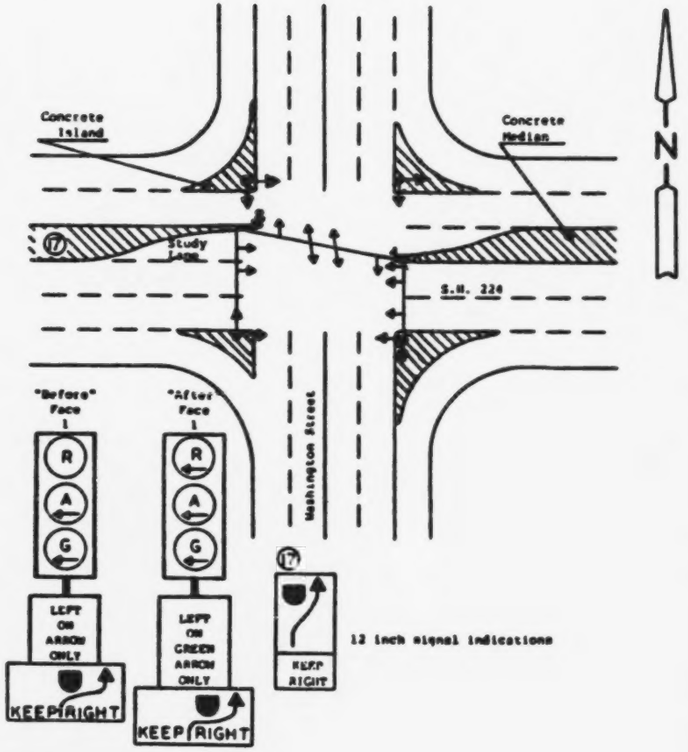

FIGURE 12: Field Site Number 35
Adams City, Colorado

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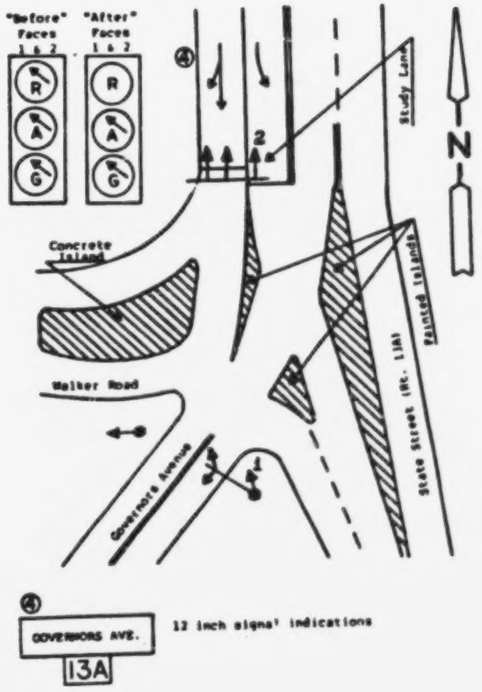

FIGURE 13: Field Site #19
Dover, Delaware

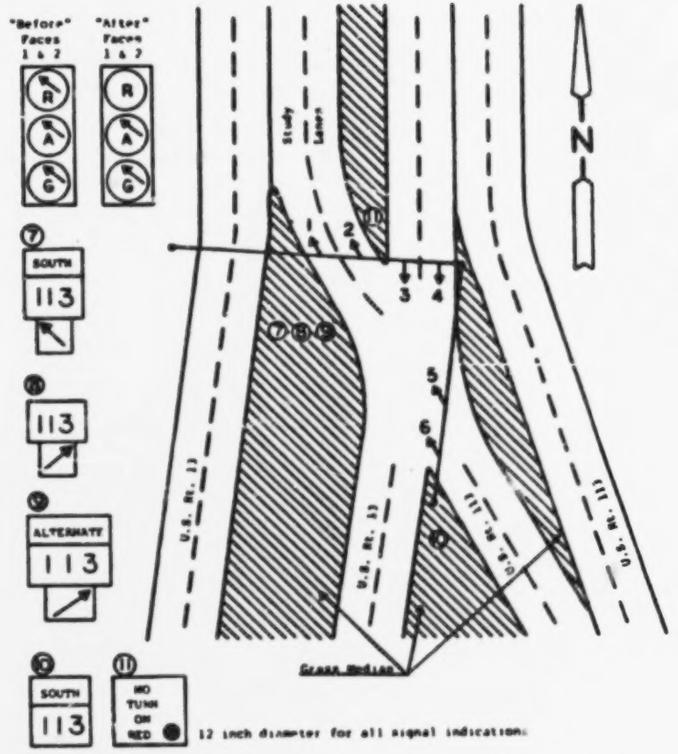

FIGURE 14: Field Site #20
Dover, Delaware

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FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH AND DEVELOPMENT

The Offices of Research and Development (R&D) of the Federal Highway Administration (FHWA) are responsible for a broad program of staff and contract research and development and a Federal-aid program, conducted by or through the State highway transportation agencies, that includes the Highway Planning and Research (HP&R) program and the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board. The FCP is a carefully selected group of projects that uses research and development resources to obtain timely solutions to urgent national highway engineering problems.*

The diagonal double stripe on the cover of this report represents a highway and is color-coded to identify the FCP category that the report falls under. A red stripe is used for category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, green for categories 6 and 7, and an orange stripe identifies category 0.

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion, and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements that affect the quality of the human environment. The goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge and technology of materials properties, using available natural materials, improving structural foundation materials, recycling highway materials, converting industrial wastes into useful highway products, developing extender or substitute materials for those in short supply, and developing more rapid and reliable testing procedures. The goals are lower highway construction costs and extended maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highways at reasonable costs,

6. Improved Technology for Highway Construction

This category is concerned with the research, development, and implementation of highway construction technology to increase productivity, reduce energy consumption, conserve dwindling resources, and reduce costs while improving the quality and methods of construction.

7. Improved Technology for Highway Maintenance

This category addresses problems in preserving the Nation's highways and includes activities in physical maintenance, traffic services, management, and equipment. The goal is to maximize operational efficiency and safety to the traveling public while conserving resources.

0. Other New Studies

This category, not included in the seven-volume official statement of the FCP, is concerned with HP&R and NCHRP studies not specifically related to FCP projects. These studies involve R&D support of other FHWA program office research.

* The complete seven-volume official statement of the FCP is available from the National Technical Information Service, Springfield, Va. 22161. Single copies of the introductory volume are available without charge from Program Analysis (HRD-3), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.

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